A methodology to constrain carbon dioxide emissions from coal-fired power plants using satellite observations of co-emitted nitrogen dioxide

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Why don't we estimate CO_2 emissions directly?

- Bottom-up approach:

$$\mathrm{CO_2\ emiss}_{[\mathrm{TgCO_2}]} =$$

$$(\mathrm{activity}_{[\mathrm{MMBtu}]})(C_{\mathrm{coeff},[\mathrm{TgC/QBtu}]})(\mathrm{oxid\ fact.})(44/12)(1 \times 10^{-9})$$

✓ physical amount of fuel consumed multiplied by the heat content of the fuel; referred to as "heat input"

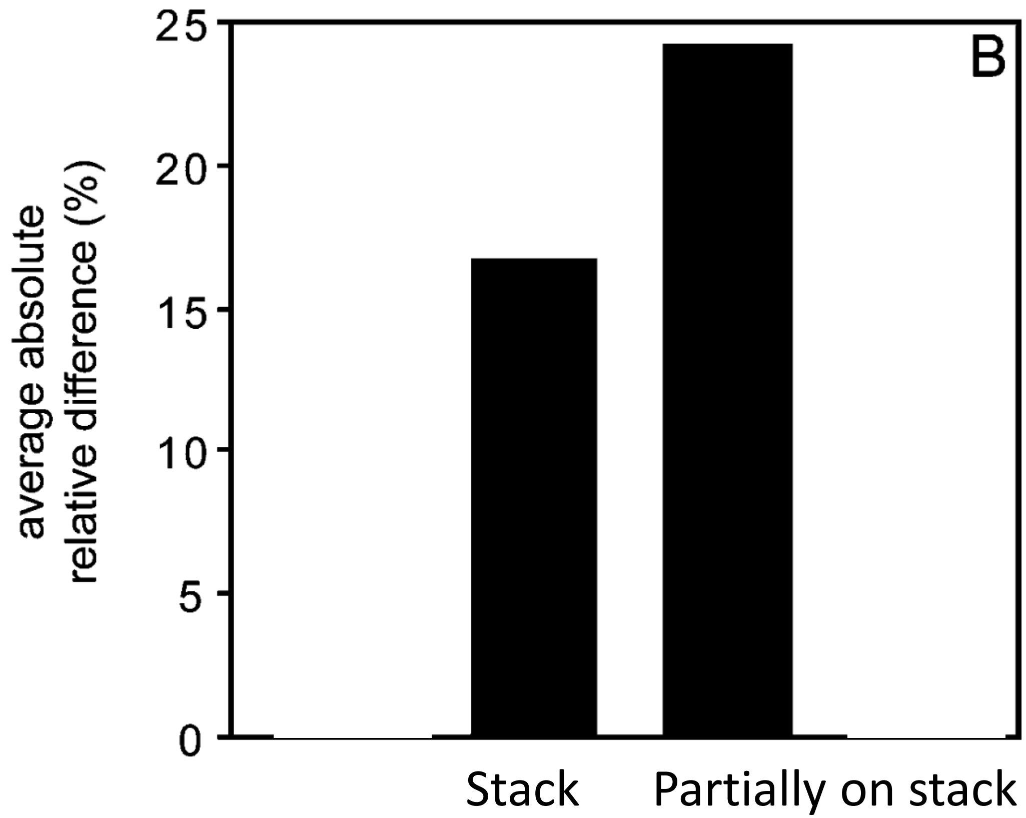
✓ carbon coefficient of each fuel: the amount of carbon released per unit of fuel energy consumed

✓ oxidation factor: the fraction of carbon that is oxidized during combustion

Uncertainty of bottom-up CO_2 emissions

Difference between EPA and EIA CO_2 emissions

average absolute relative difference between EPA and EIA CO_2 emissions reported for individual power plants for 2004



Ackermann and Sundquist (2008)

- Both the Department of Energy's Energy Information Administration (EIA) and the Environmental Protection Agency (EPA)'s eGRID database report CO_2 emissions for individual power plants in the US
- EIA emissions are based on **fuel data**
- EPA eGRID uses 3 monitoring methods: **stack measurement, calculation from fuel data, or a combination of the two methods**
- Estimates that are based partly or entirely on monitoring of stack gases (EPA) differed significantly from estimates based on fuel consumption (EIA).

"direct" CO_2 emissions estimates

- Bottom-up approach:

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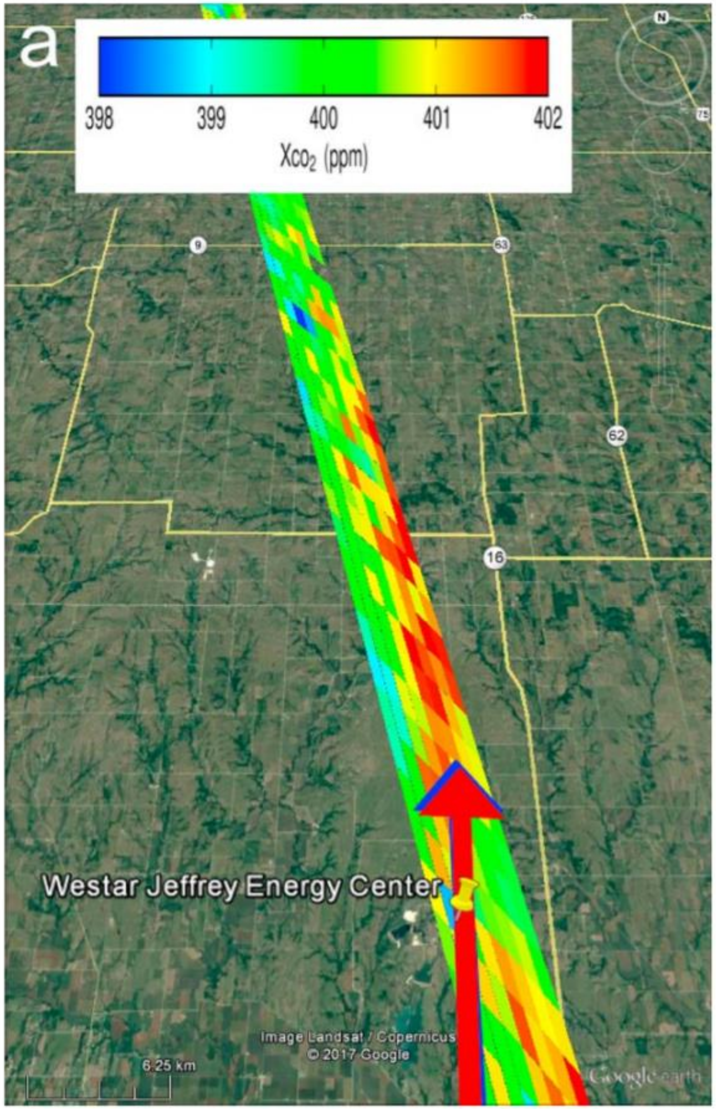
- Top-down approach:

✓ Satellites provide retrievals of CO_2 vertical columns in terms of the CO_2 column-averaged dry-air mole fraction, denoted by XCO_2

using XCO_2 to quantify emissions

XCO_2 from OCO-2



- None of the existing satellite CO_2 sensors has been designed to monitor anthropogenic CO_2 emissions
- There is only a very small number of good OCO-2 overpasses for a given power plant (best case: 17 overpasses out of 2-year data)
- Estimating annual emissions requires multiple clear-sky revisits in a given year, which is likely not possible to obtain routinely from a single LEO mission

Ray et al. (2017)

“indirect” CO_2 emissions estimates: methodology

$$E_{CO_2,y}^{Sat} = \frac{E_{NO_{x,y}}^{Sat}}{ratio_{i,y}^{CEMS}}$$

OMI NO_2 observations

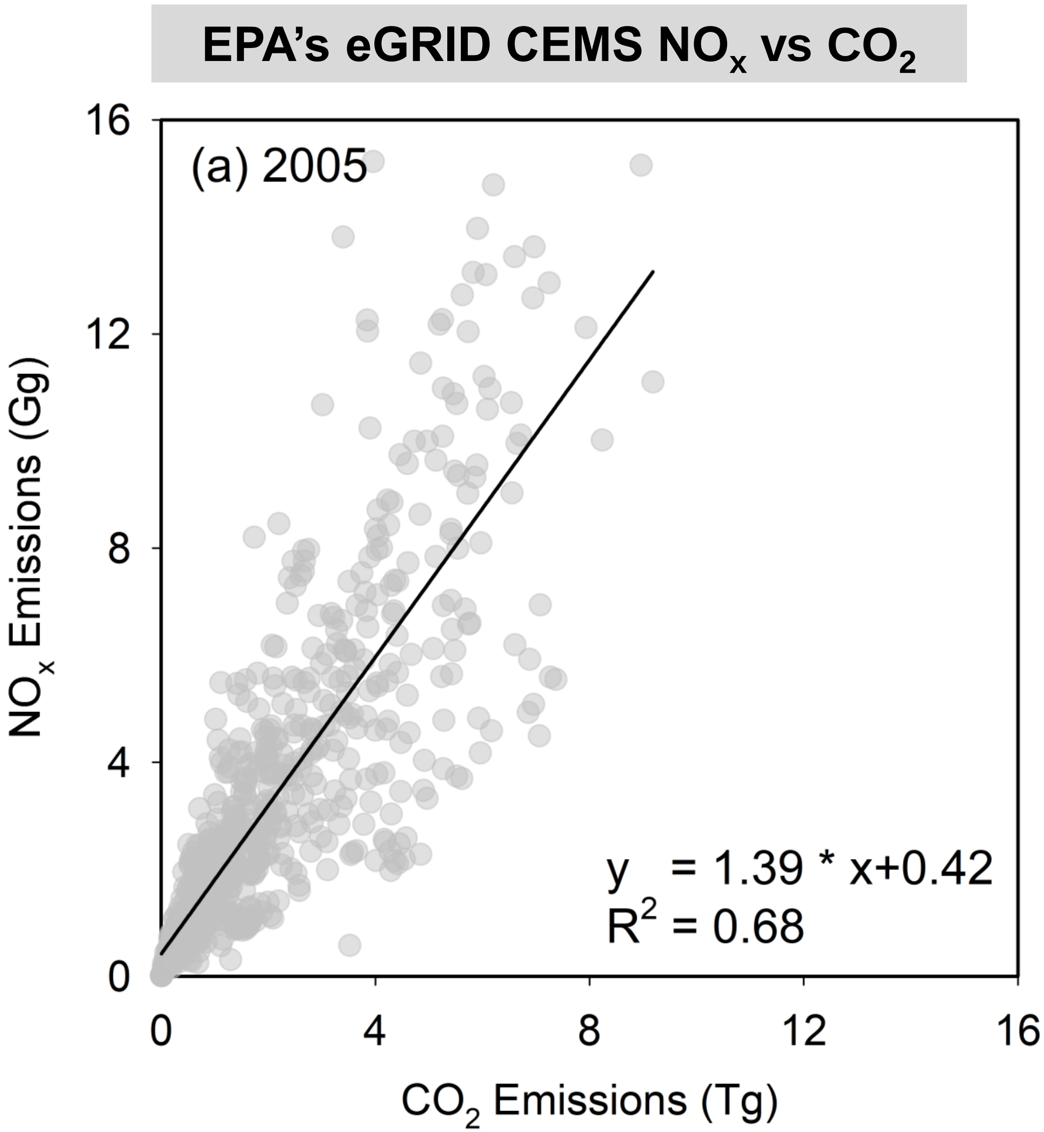
CEMS CO_2 and NO_x emissions

- E_{CO_2} and E_{NO_x} represent the satellite-derived CO_2 and NO_x emissions, respectively.
- Ratio represents the ratio of NO_x to CO_2 emissions for power plants

Infer NO_x emissions based on OMI NO_2 observations:

Liu, F., Beirle, S., Zhang, Q., Dörner, S., He, K., and Wagner, T.: NO_x lifetimes and emissions of cities and power plants in polluted background estimated by satellite observations, Atmos. Chem. Phys., 16, 5283–5298, doi: 10.5194/acp-16-5283-2016, 2016.

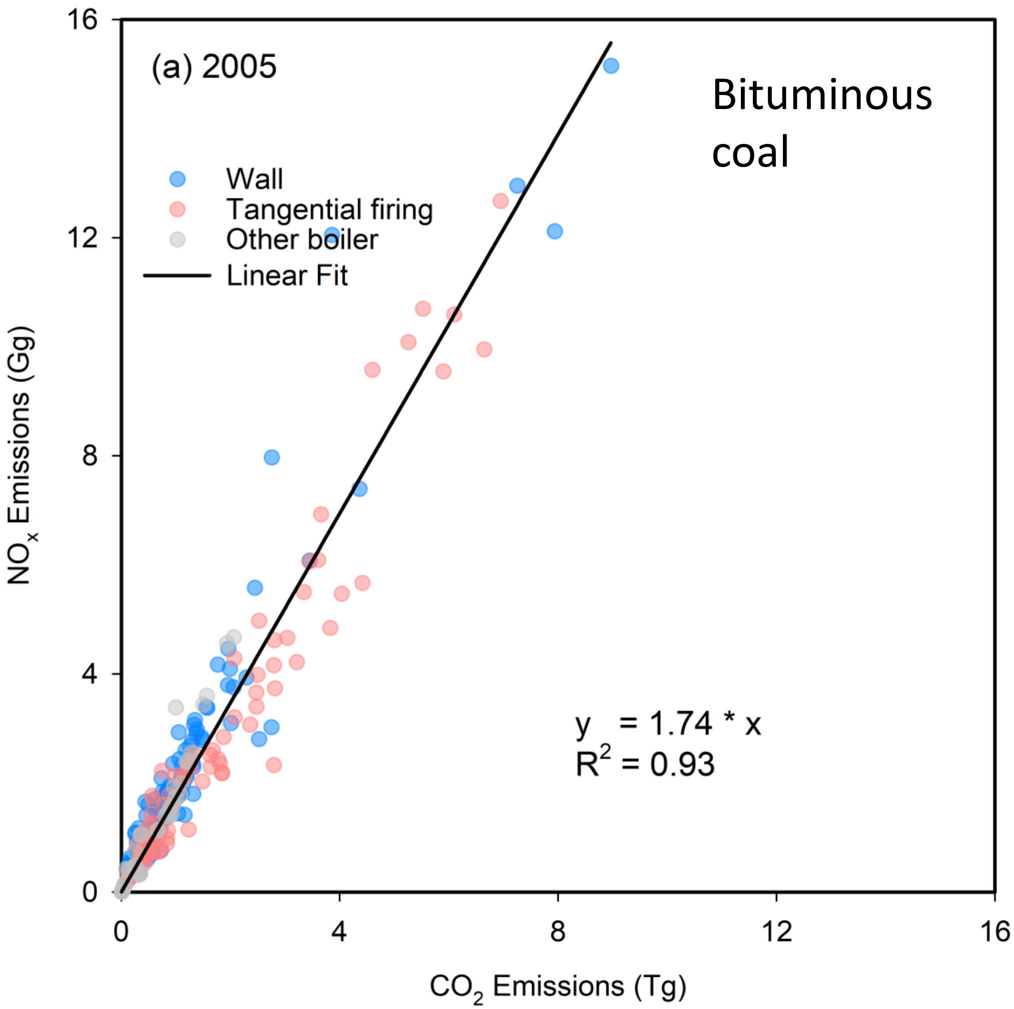
The ratio of NO_x to CO_2 for the US power plants



- NO_x emission factors vary by coal type, firing type, and emission control device type
- For power plants installing post-combustion NO_x controls (i.e., selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR)), NO_x emission factors vary widely, as NO_x removal efficiency is plant-specific

The ratio of NO_x to CO_2 for the US power plants

EPA's eGRID CEMS NO_x vs CO_2



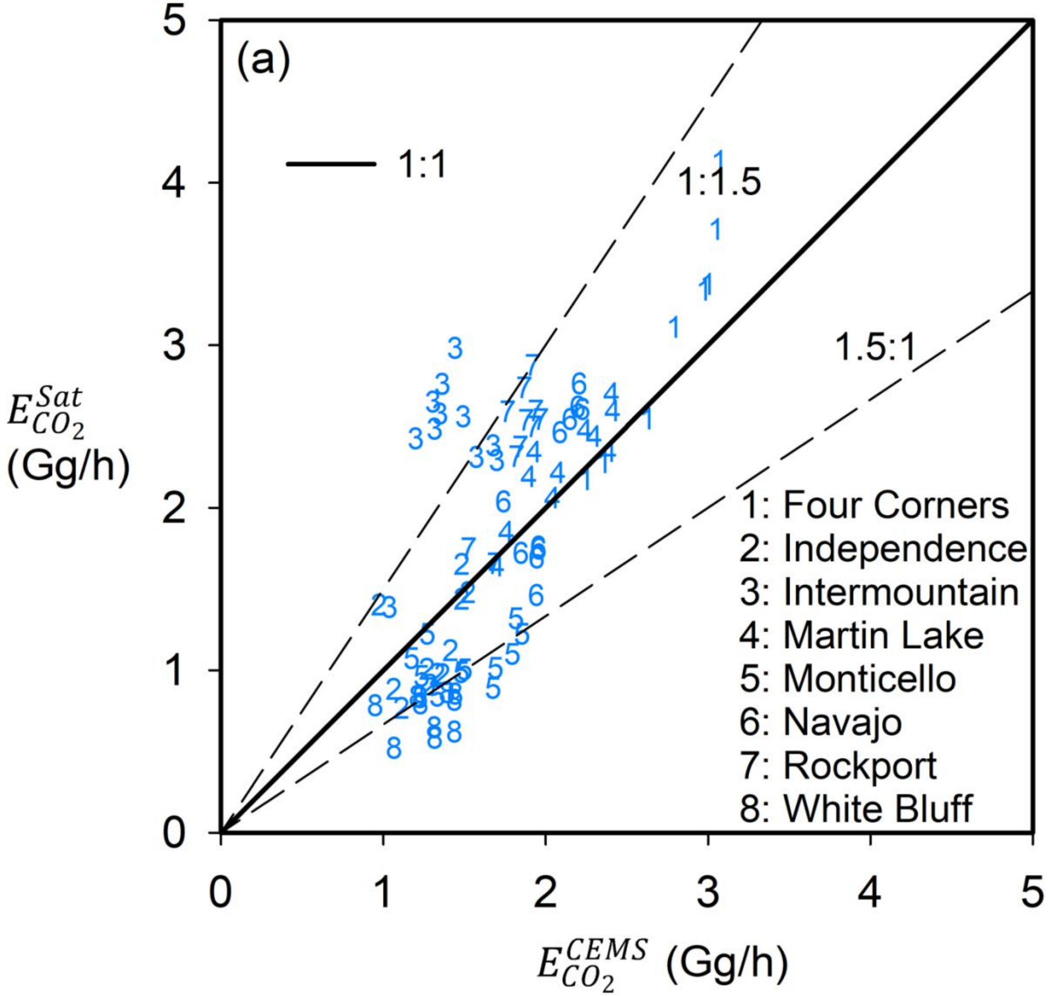
- Only power plants without installing post-combustion NO_x controls are considered
- Calculate NOx/CO_2 emissions by coal type
- CO_2 emissions show linear correlation with NO_x emissions

ratio of NO_x to CO_2 emissions by coal type

Investigated power plants

- We chose these plants based on $E_{NO_x}^{CEMS}$ (i.e., > 10 Gg/yr in 2005) and relative isolation from other large sources to avoid contamination of a power plant's NO_x plumes by NO_x from other sources.
- From all US coal-fired power plants, we selected 21 power plants for estimating $E_{NO_x}^{Sat}$.
- we are able to estimate $E_{NO_x}^{Sat}$ for 8 of the 21 plants.

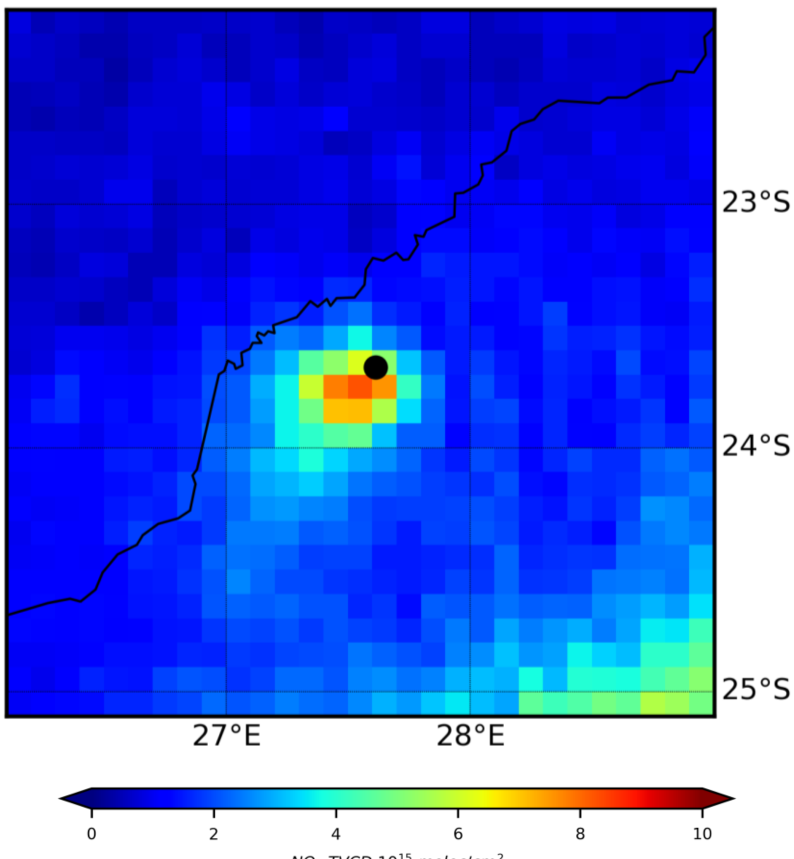
CO_2 emissions based on OMI-based NO_x emissions



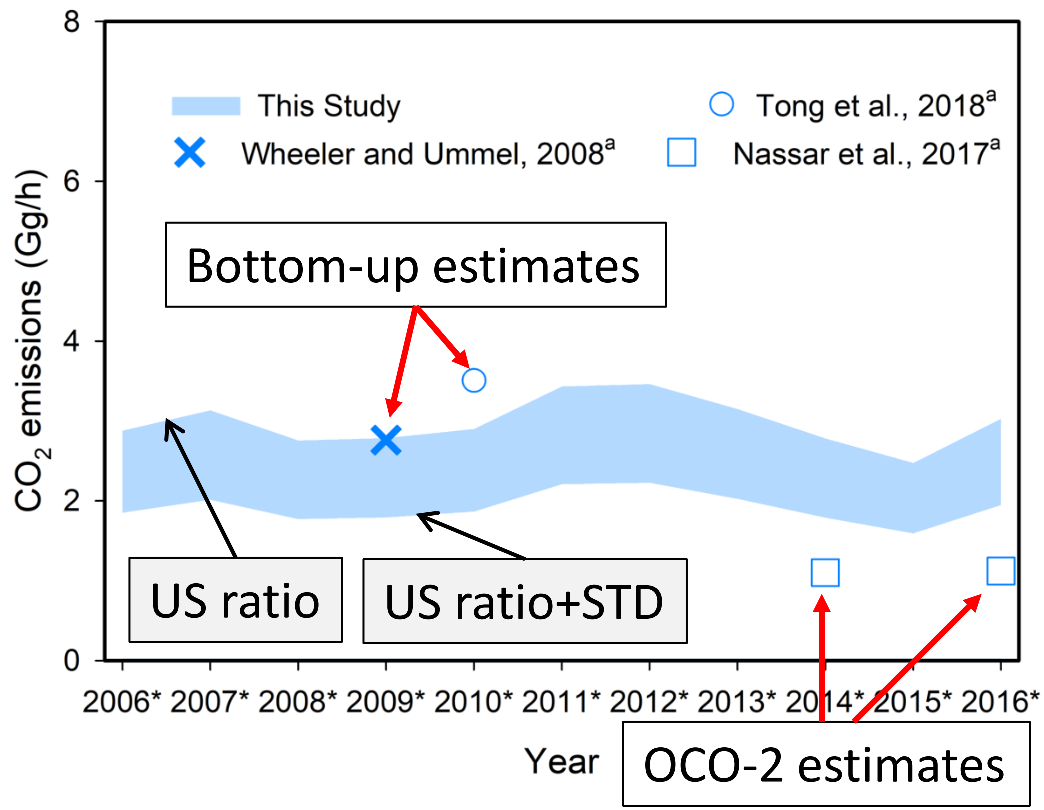
- The comparison shows a correlation, R^2, of 0.66
- relative difference for individual 3-year means (defined as $(E_{CO_2}^{Sat} - E_{CO_2}^{CEMS})/E_{CO_2}^{CEMS}$) is 8% ± 41% (mean ± standard deviation)

Case study in South Africa

Matimba power plant



Compare with other estimates



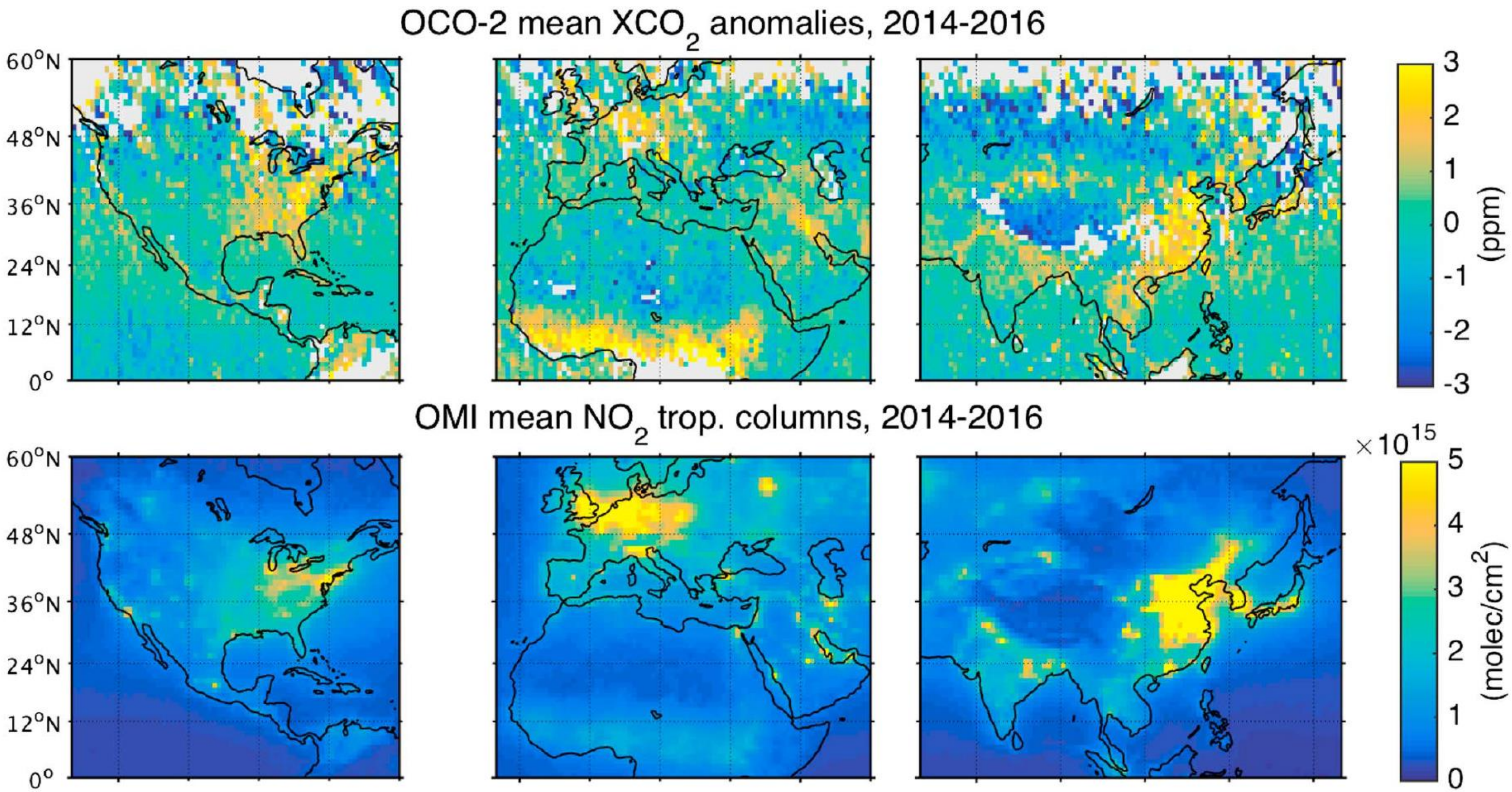
- Matimba uses subbituminous coal
- Use the ratio ranging from 2005 $ratio_{regressed}^{CEMS}$ to 2005 $ratio_{regressed}^{CEMS}$ + standard deviation for subbituminous coal to infer $E_{CO_2}^{Sat}$ based on $E_{NO_x}^{Sat}$, because the power plant is not equipped with any NO_x control devices, even low-NO_x burners which are widely installed in US power plants

Take home messages

- The NO_x-to-CO_2 emissions vary by coal types
- The OMI-based CO_2 emissions for the US power plants show reasonable agreement with EPA CEMS measurements
- The approach shows the capability to provide constraint on CO_2 emissions for regions outside the US

Can we infer CO_2 from NO_2?

NO_2: the co-emitted species of CO_2

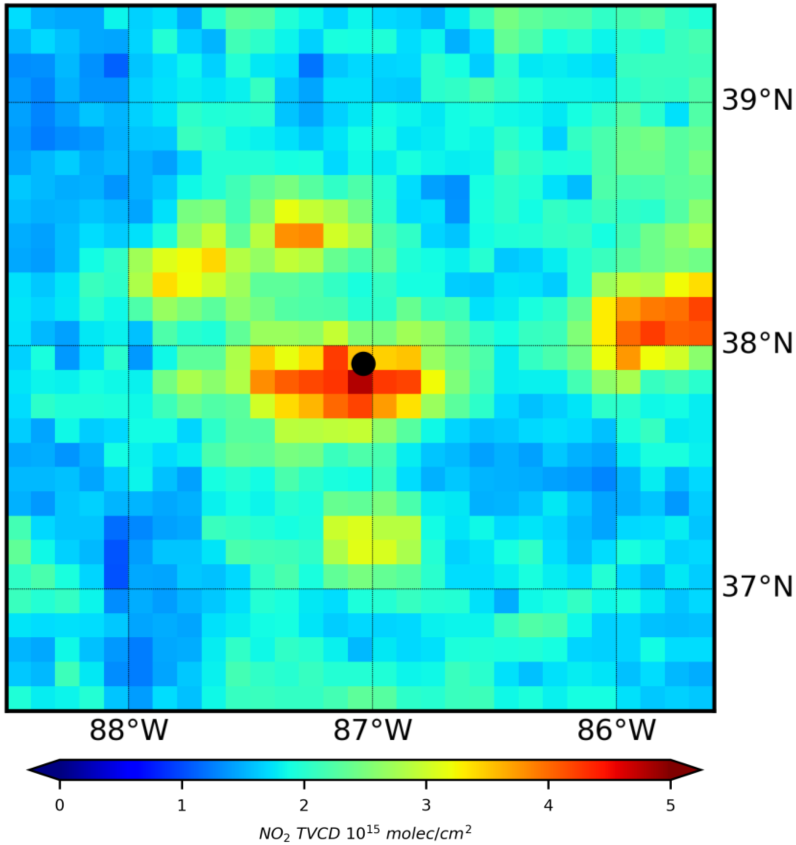


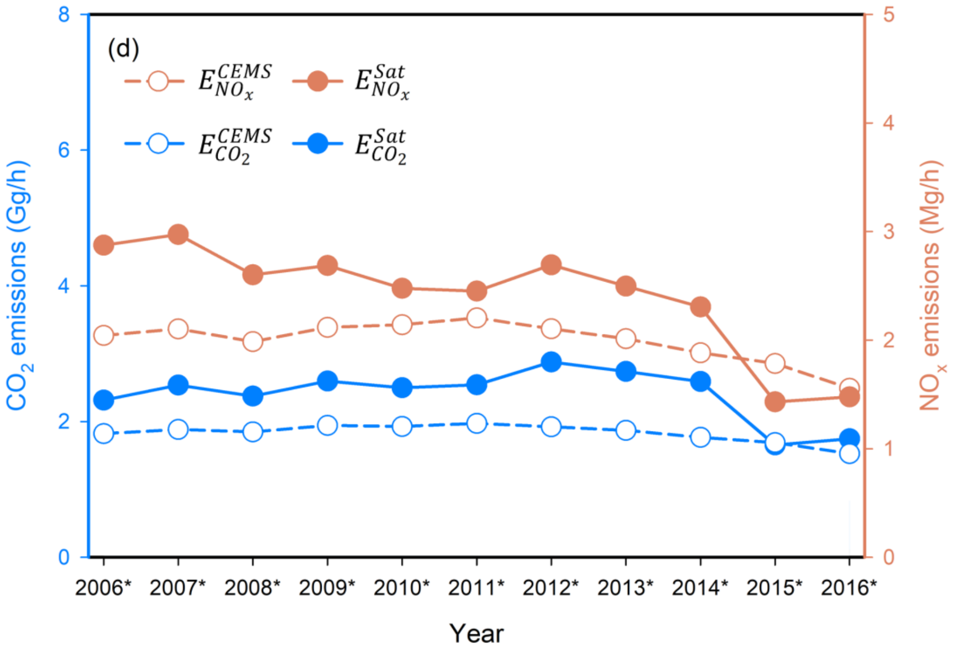
- The mean XCO_2 anomalies match the spatial distribution of the mean NO_2 tropospheric columns observed by OMI

Hakkarainen et al. (2016)

CO_2 emissions based on OMI-based NO_x emissions

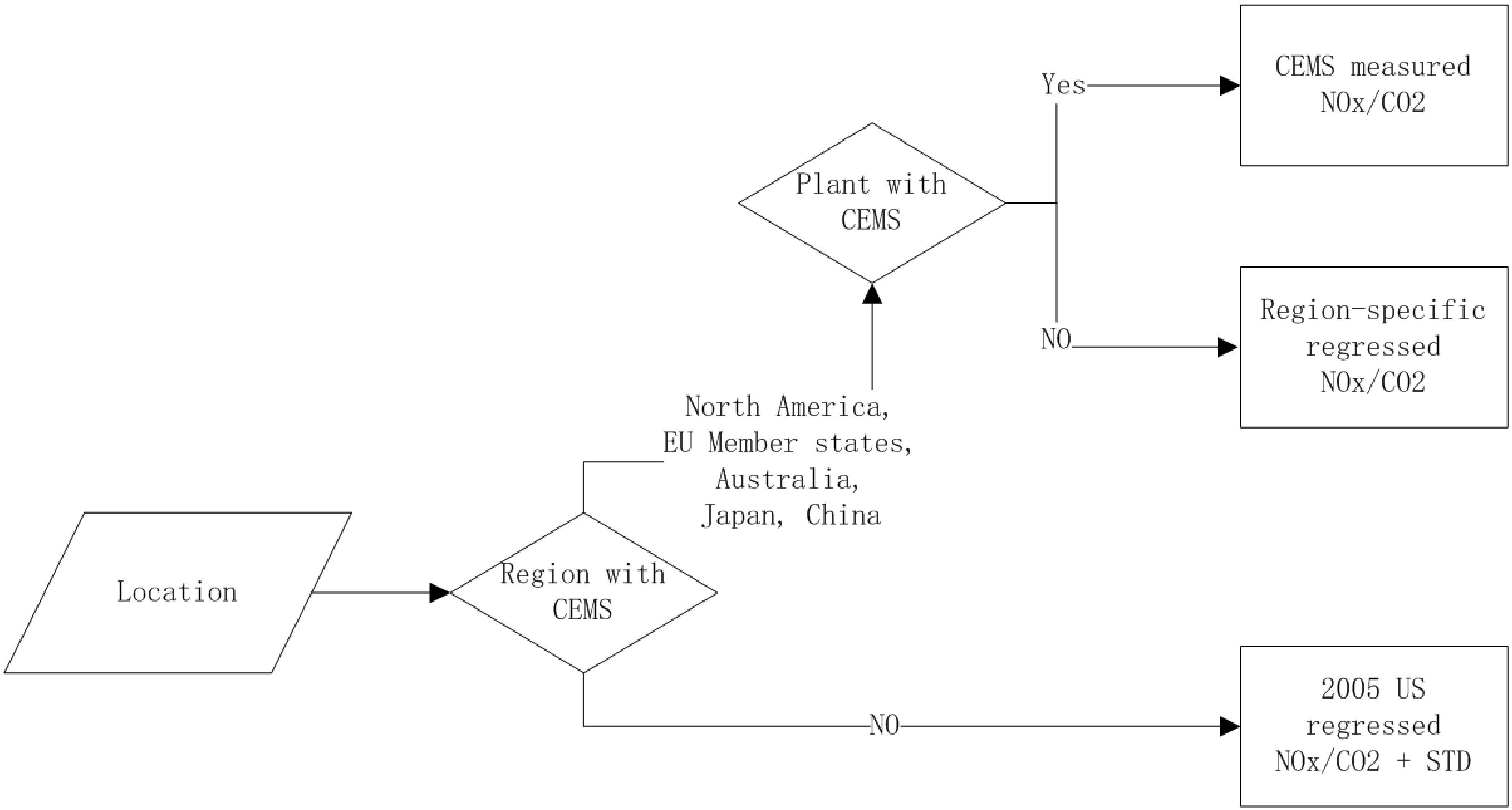
Rockport power plant



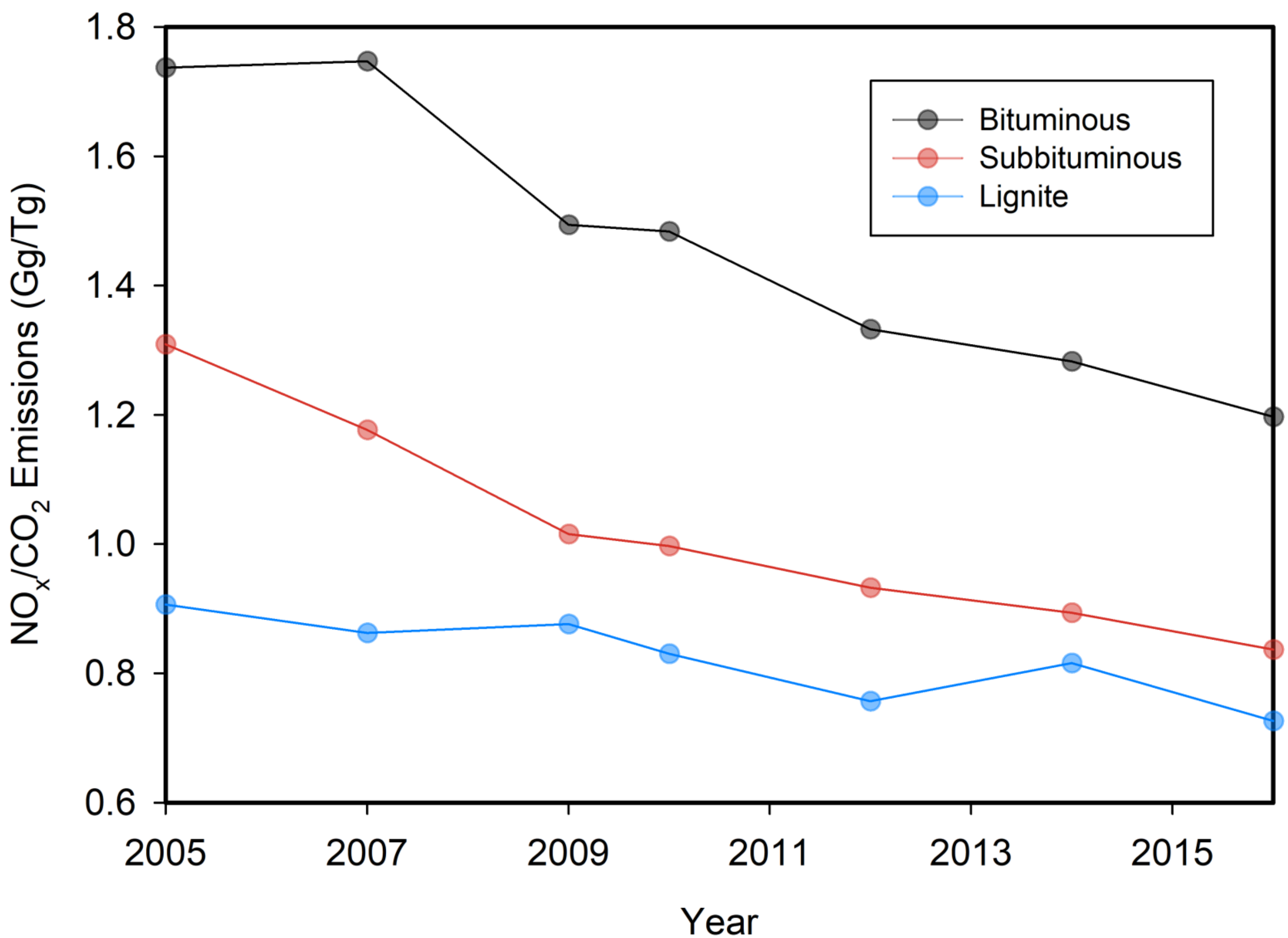


- Quantify NO_x emissions based on the averaged OMI NO_2 TVCDs averaged over 3 years
- Quantify CO_2 emissions based on the ratio of NO_x to CO_2 derived from the CEMS measurements

Application



Trend of the ratio of NO_x to CO_2



- The ratio is changing gradually driven by the improved performance of the NO_x combustion controls

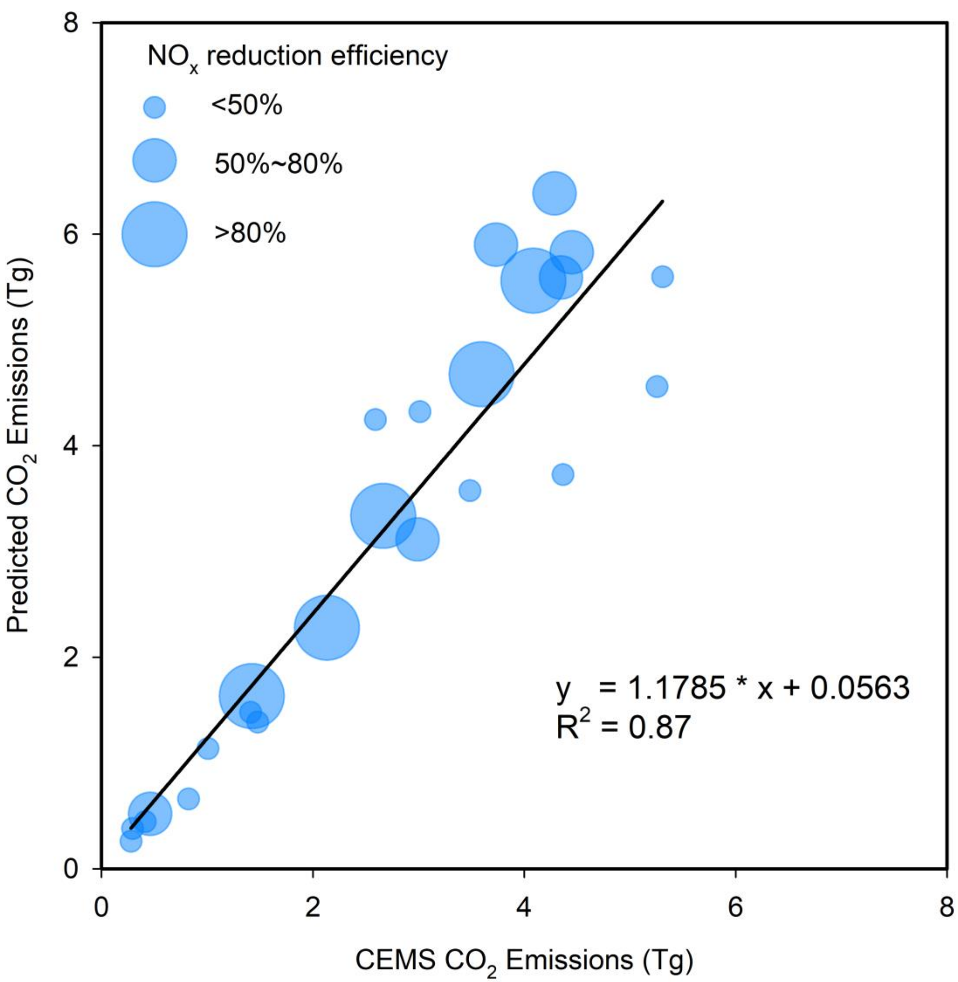
Adjusted ratio

$$ratio_{i,y}^{CEMS-Estimated} = ratio_{regressed,i,y}^{CEMS} \times (1 - f_y)$$

- Techniques used to reduce NO_x emissions are classified into two fundamentally different methods: combustion controls (e.g., low NO_x burners) and post-combustion controls (i.e., selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR))
- $ratio_{regressed,i,y}^{CEMS}$ represents the ratio of NO_x to CO_2 emissions for power plants before plumes go through SNCR/SCR
- For units installing post-combustion controls, NO_x/CO_2 emissions vary widely
- f represents the removal efficiency of the post-combustion NO_x control system. If no post-combustion technique is applied, f is set to zero.

Estimate the CO_2 emissions for power plants installing post-combustion control devices

We select all units using post-combustion controls in 2016, but not in 2005, to demonstrate the approach

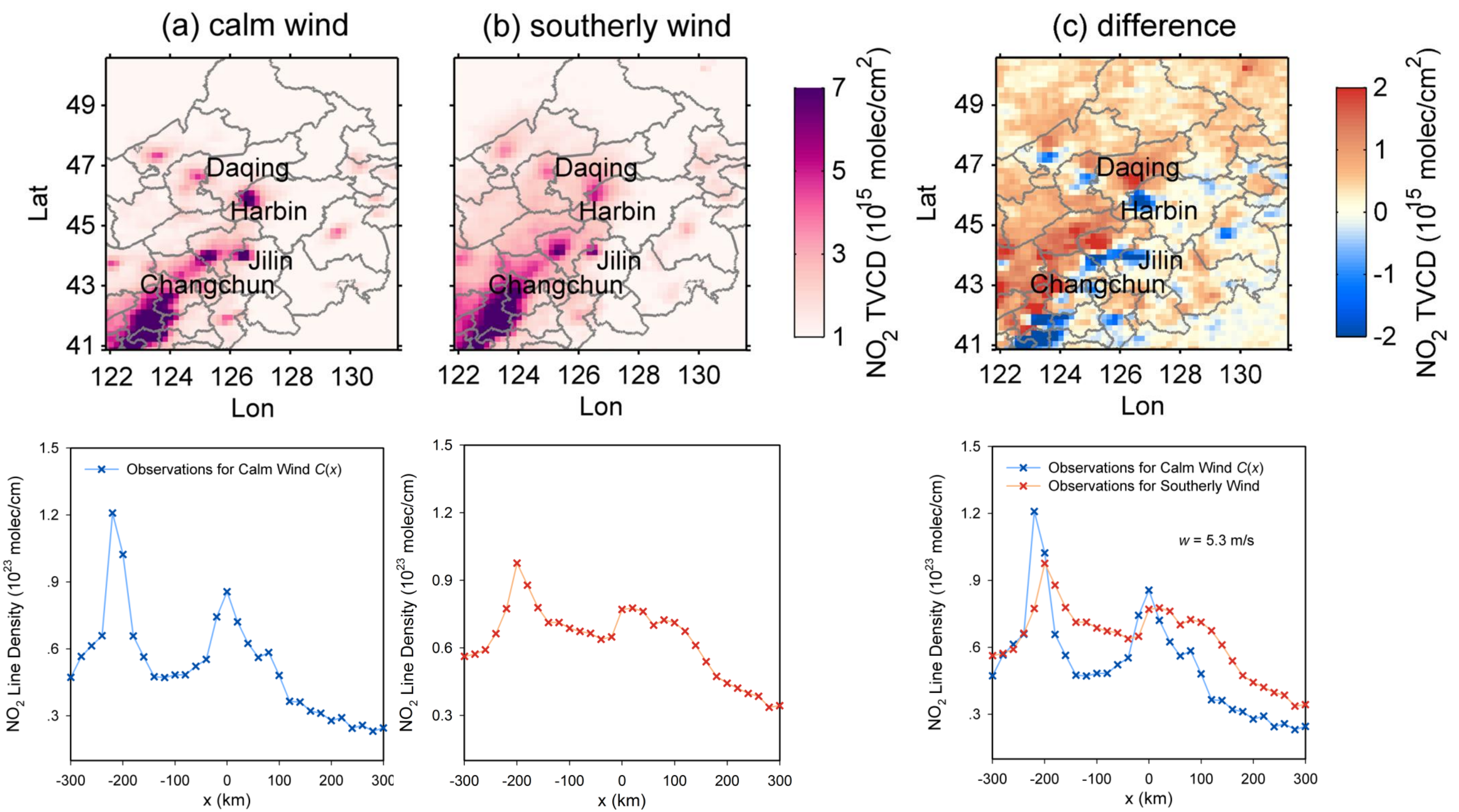


For power plants using postcombustion controls:

- NO_x reduction efficiency is derived from EPA's eGRID database
- Estimate unabated NO_x emissions based on CEMS NO_x emissions
- CO_2 emissions based on the regressed ratio of NO_x to CO_2 emissions are consistent with the CEMS CO_2 emissions

NO_x emissions based on OMI NO_2 columns

2005–2013 OMI NO_2 Average



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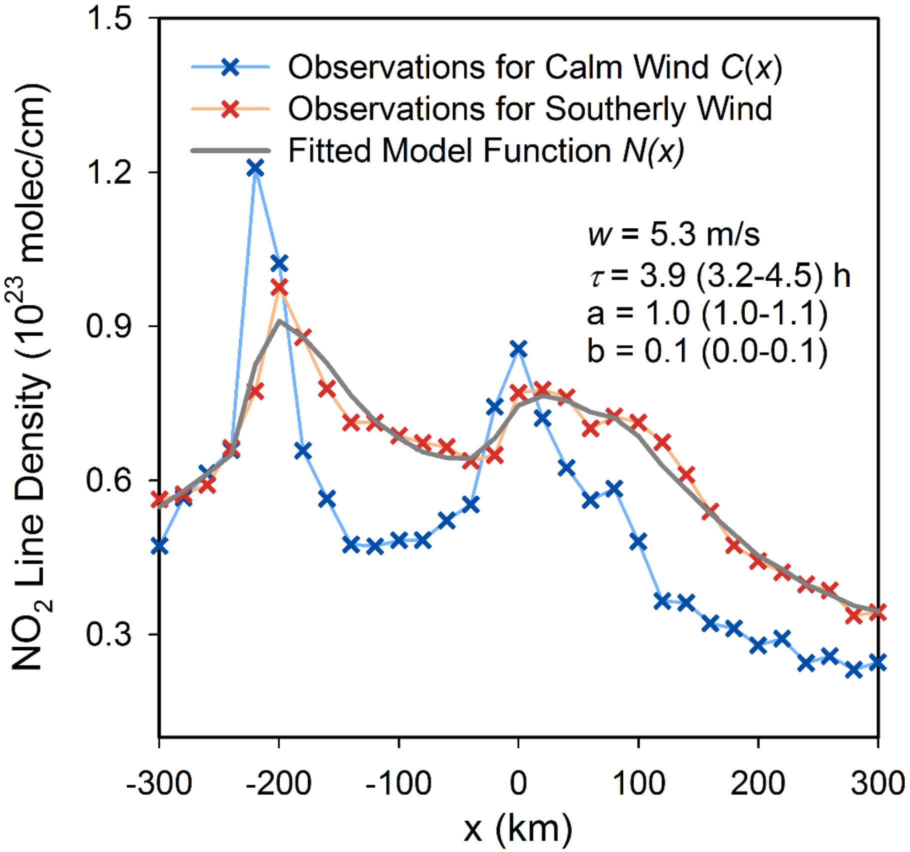
NO_x emissions based on OMI NO_2 columns

- Use the NO_2 distribution for calm wind conditions C(x) as proxy for the spatial distribution of NO_x sources

- model function:

$$N(x)=a(e\otimes C)+b$$

- E= total mass / lifetime



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Uncertainty of XCO_2

- Satellites provide retrievals of CO2 vertical columns in terms of the CO2 column-averaged dry-air mole fraction, denoted by XCO2
- Existing or planned satellite instruments for measuring greenhouse gases with high near-surface sensitivity such as SCIAMACHY on ENVISAT or TANSO on the Greenhouse Gases Observing Satellite (GOSAT) aim primarily at providing additional constraints on natural CO2 sources and sinks. None of the existing satellite CO2 sensors has been designed to monitor anthropogenic CO2 emissions
- The capacity of GOSAT and OCO-2 observations to detect anthropogenic CO2 emissions from point sources is limited